Assessing pedestrian’s thermal transient condition: a bottom-up simulation approach

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ABSTRACT: Effective assessment of pedestrian’s thermal comfort has been a continuous endeavour in urban climatology studies. A number of bio-meteorological indices such as PMV, OUT-SET* and PET have been developed aiming to describe human’s thermal comfort sensation by providing solutions to the equations governing their thermoregulations. A drawback of this approach is that these indices are based on steady-state models and therefore can not effectively account for pedestrian’s thermal transient process. In fact, studies have shown that steady-state models will cause problems when applied in outdoor pedestrian thermal comfort assessment. This study presents a bottom-up simulation approach which considers pedestrian’s dynamic and behavioural aspects in assessing their thermal comfort conditions. A promising modelling technique, the agent-based modelling (ABM) approach is taken to model each individual pedestrian’s detailed thermoregulatory characteristics and also movement behaviours. A modified Two-Node Model is used to model pedestrian’s progressive thermal adaptation to the local microclimatic condition. With a test case the study shows that the modelled thermal transient is significantly different from the static assessment as indicated by PET, suggesting that a combinatorial use of pedestrian’s detailed thermoregulatory parameters is a more appropriate way to describe their actual thermal comfort condition. The present individual-based simulation approach also allows different group of pedestrian’s to be examined and also different environmental scenarios to be tested.

Conference theme: Sustainability Issues
Keywords: thermal comfort, dynamic adaptation, agent-based simulation

1. INTRODUCTION

Outdoor thermal comfort is of prime importance in town planning. In the global context of climate change and rapid urbanization, ensuing that people outdoors are not suffering from thermal stress is a must for high-quality urban living. A major task in this aspect is to design buildings and outdoor spaces that promote pedestrian’s thermal comfort and therefore are well used. Climatic understanding is essential in this context. As stated in the report by the American Society of Civil Engineers: “The usefulness and attractiveness of outdoor areas near buildings are greatly affected by the local climate.” (Task Committee on Outdoor Human Comfort of the Aerodynamics, 2004) To fulfil the task, it is crucial to assess the influence of the outdoor microclimate on people’s thermal comfort.

On the other hand, effective assessment of outdoor thermal comfort is both a research and a practical challenge. Traditional bio-meteorological indicators such as the Predicted Mean Vote (PMV) (Fanger, 1982) only work for steady-state subjects, therefore are not suitable for pedestrians who are dynamic and seldom reach steady-state. Evaluation methods are also absent in taking into account people’s individual activity and response. The present paper proposes a bottom-up simulation approach which models each individual pedestrian’s thermal transient condition using a modified Pierce Two-Node model.

2. BACKGROUND

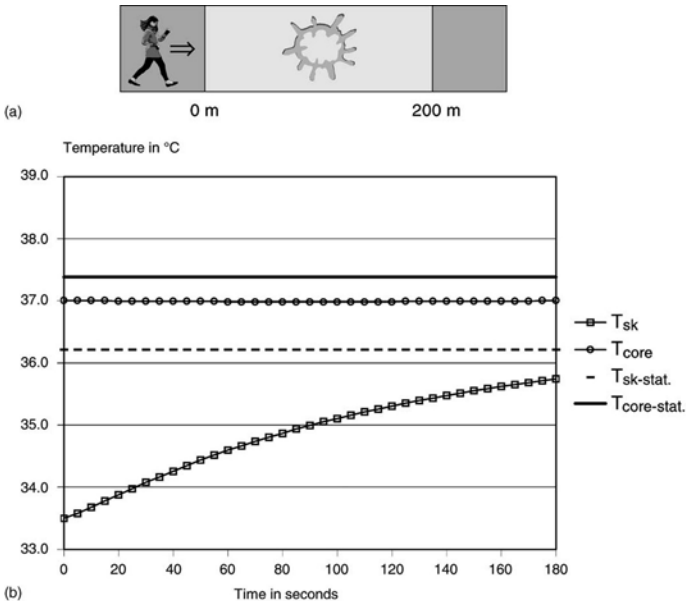
2.1. Thermal comfort models

A number of biometeorological indices have been developed over the past decades to describe human thermal comfort by linking local microclimatic condition and human thermal sensation (Task Committee on Outdoor Human Comfort of the Aerodynamics, 2004). One of the most widely used indices is PMV. PMV predicts the mean response of a large population of people and is often measured by a seven-point thermal sensation scale that ranges from -3, meaning cold, to +3, meaning hot. Another commonly used form of PMV is the Predicted Percentage Dissatisfied Index (PPD), which is defined as the quantitative prediction of the percentage of thermally dissatisfied people at each PMV value. PMV has been included in the ISO standard (ISO, 1994). PMV was firstly developed as an indoor thermal comfort index, but it has also been commonly adopted in outdoor thermal comfort studies (Cheng, Ng, Chan, & Givoni, 2010; Nikolopoulou, Baker, & Steemers, 2001).

Another notable index is the Physiological Equivalent Temperature (PET) (Mayer & Höppe, 1987). As compared to PMV, PET is a temperature dimension index measured in degree Celsius. It is defined as the air temperature at which, in a typical indoor setting, the human energy budget is maintained by the skin temperature, core temperature, and sweat rate equal to those under the conditions to be assessed (Höppe, 1999). Because of its temperature dimension representation, PET can be easily understood and interpreted by people without sufficient meteorological domain knowledge. It has been widely applied in outdoor thermal comfort studies in various climates (Ali-Toudert & Mayer, 2006; Matzarakis, Mayer, & Iziomon, 1999; Thorsson, Honjo, Lindberg, Eliasson, & Lim, 2007). And there are other evaluation methods such as the OUT-SET* (Pickup & De Dear, 1999) and the Universal Thermal Climate Index (UTCI) (Jendritzky, Maarouf, & Staiger, 2001). These models all serve as analytical tools to assess human thermal responses to the local thermal environment.

2.2. Problem with steady-state models

The aforementioned indices are all based on steady-state models, meaning that the resulted values indicate the thermal comfort condition of the subject after he/she has reached thermal equilibrium condition. For pedestrians outdoors, this pre-assumption is hardly true, as walking involves transient process and dynamic and temporal thermal adaptation. In such a case, the use of steady state indices will normally cause problems in assessing pedestrians' "actual" thermal sensation. Indeed Höppe (2002) has explicitly shown the difference between a pedestrian's dynamic thermal adaptation and the theoretical steady state condition using a simple "sunny street segment" case (Figure 1). And the use of such steady-state models, such as PMV, in outdoor thermal comfort studies has been proved unsuitable (Nikolopoulou, et al., 2001).



Source: (Höppe, 2002)

Figure 1: An illustration showing the difference between a pedestrian's dynamic thermal adaptation and the steady state condition: (a) scenario "sunny street segment"; (b) temporal variation of pedestrian's physiological conditions, described by skin temperature (T_{sk}) and core temperature (T_{core}). $T_{sk\text{-}stat}$ and $T_{core\text{-}stat}$ are steady state skin temperature and core temperature, respectively. Source: (Höppe, 2002)

As opposed to the various indicators developed to assess steady-state human thermal comfort, the methodologies for dynamic assessment show a scattered picture. Most methods for assessing human dynamic thermal adaptation are based on the Pierce Two-Node Model (TNM) (Gagge, Stolwijk, & Nishi, 1971). As the name implies, this model treats the human body as two isothermal parts, skin and core, based on which the thermoregulation, i.e., heat exchange equations are constructed for the passive state. Effectively, core temperature, skin temperature and mean body temperature can all be derived by their deviation from the set points. Other thermoregulatory indicators such as sweating rate and skin blood flow can also be evidently defined. Notably today's commonly used TNMs are based on a substantial update of the initial model (Gagge, Fobelets, & Berglund, 1986). Different computer implementations of TNM was reviewed in (Fountain & Huizenga, 1995), including computer programs written in programming languages such as FORTRAN, Basic and C++. The model has been continually expanded, such as considering the impact of the wind environment (Parsons, Havenith, Holmér, Nilsson, & Malchaire, 1999), implementation of 3-D representation of human body to respond to complex urban environment (Huizenga, Zhang, & Arens, 2001), introducing additional parameters of individual properties such as body composition or acclimatization status (Havenith, 2001), and expanding the two-node model to multi-node models representing different body parts (Foda & Sirén, 2010). In the present study, TNM is selected as the tool for assessing pedestrian's thermal transient condition.

3. METHODOLOGY

A computer simulation system is implemented to model each individual pedestrian's movement in the urban environment and thermal transient from bottom-up. In contrast with the traditional top-down modelling paradigms, this individual-based modelling approach, commonly named as *agent-based modelling*, characterizes a system by looking at its constitutional units – the agents. This promising modelling technique is particularly suitable for the objective of this study in that it allows detailed examination of a person by connecting his/her thermal transient condition with the local climatic condition. The idea of agent-based modelling of pedestrian's thermal comfort is largely inspired by the BOTworld system by (Bruse, 2007). However the major conceptual difference is that, in the present system, a person agent behaves and is analysed in a real world -like comprehensive urban context as opposed to the rasterized grid space in BOTworld. The system defines the immediate climatic environment the pedestrian is exposed to, including air temperature, wind speed, solar radiation, etc. The pedestrian's personal properties, such as body weight and walking speed, are also defined or generated in the system. The software structure of the system and the pedestrian simulation module are not the focus of this paper, and interested readers are referred to (Chen, 2011) for details. The implementation of the TNM is presented in this paper.

3.1. Implementation of TNM

The computer program written in C++ programming language published in (Fountain & Huizenga, 1995) is used in this study. The program is rewritten in Java programming language and implemented as an object of a person agent. The model is modified to account for the wind environment based on (Parsons, et al., 1999). Notably the biggest change made to the original program is that a "temporal" characteristic is added: the model is integrated with the movement control of a person agent, allowing the temporal update along with the agent's spatial variation. Due to page limitation, only main formulas are presented here. Table 1 gives a summary of the input parameters in TNM.

Table 1: Summary of input parameters used in TNM.

Personal attributes		Meteorological parameters	
temporally-static	temporally-dynamic	spatially-constant	spatially-variant
age	speed	air temperature	solar radiation
gender	location	humidity	wind speed
body weight			
height			
clothing index			

Apart from the common parameters as listed in Table 1, there are a few other parameters of TNM that need to be selected properly. The first is the initial neutral state of human body, described as set point in TNM. In the present model, a person agent is set to have a skin temperature (T_{skin}) of 33.7°C and a core temperature ($\mathrm{T_{core}}$) of 36.8°C, as the neutral state of human body. Similar setting is also selected by (Höppe, 2002). The second parameter is the Body Surface Area (BSA), which is needed for modelling the skin thermoregulation. In practice, the commonly applied Mosteller's formula (Mosteller, 1987) is adapted, which is

$$\mathrm{BSA(m^2)} = (\mathrm{[height(cm)} \times \mathrm{weight(kg)\,]/3600})^{1/2} \qquad (1)$$

where height and weight are a person's height and weight parameters respectively. The last one is the person's metabolic rate, measured in the unit of MET (the Metabolic Equivalent of Task). According to (Ainsworth, et al., 2000), when a pedestrian is walking on a level firm surface, his/her metabolic rate can be estimated by the following relations:

2 METs: walking at 2 miles per hour (0.9m/s)

5 METs: walking at 5 miles per hour (2.2m/s)

In the system, pedestrian's walking speed is normally between 1m/s to 1.5m/s, in which case an estimated metabolic rate of 3 METs is selected. On the other hand, the relative wind speed a walking person experiences is calculated by

$$WS_{re} = \frac{\overrightarrow{V_{wind}} \bullet \overrightarrow{V_{walk}}}{|\overrightarrow{V_{walk}}|} \qquad (2)$$

where $\overrightarrow{V_{wind}}$ is the actual wind velocity, $\overrightarrow{V_{walk}}$ is the person's walking velocity.

After the parameters have been properly defined, in TNM, the net radiant heat loss from the body surface as determined by clothing is governed by

$$\mathrm{RS} = f_{frac} \cdot f_{acl} \cdot \sigma \cdot \varepsilon \cdot ((T_{cl} + 273.15)^4 - (T_{mrt} + 273.15)^4)) \qquad (3)$$

where

f_{frac} is the fractional body surface area exposed to the thermal environment, and the value of 0.725 is suggested by (Fanger, 1982) for a standing person;

f_{acl} is the increase in body surface due to clothing, and a correction is made considering the walking effect of a person on the intrinsic clothing insulation I_{cl} using the equation proposed by (Havenith, Holmér, & Parsons, 2002);

σ is the Stefan-Boltzman constant, value is $5.67 \cdot 10^{-8}$ W/m^{2}K^4;

ε is the skin emissivity, estimated as 0.98;

T_{cl} is the clothing temperature;

and T_{mrt} is the mean radiant temperature.

The model calculates T_{cl} in a iterative manner. At each iteration step, T_{cl} is estimated by:

$$T_{cl} = (T_{skin} / I_{cl} + f_{acl} \cdot (h_c \cdot T_a + h_r \cdot T_{mrt})) / (1 / I_{cl} + f_{acl} \cdot (h_c + h_r)) \qquad (4)$$

where T_a is the air temperature, h_c is the convention heat transfer coefficient, h_r is the radiant heat transfer coefficient. In this way, transient T_{skin}, T_{core}, and other thermoregulatory parameters can be calculated by their temporal deviation from the set points. In the model, a updating time interval ranging from 1 sec to 1 min can be selected.

4. RESULTS

4.1. Verification

Because of the newly added timely updating function, the implementation of TNM needs to be verified properly to ensure that the model has been re-programmed correctly. Therefore, the model is cross-tested with The *WWW Thermal Comfort Index Calculator* by de Dear (N/A). The air temperature T_a is set to be 30°C, and the Mean Radiant Temperature (T_{mrt}) is set to be 42°C, and the relative humidity is set to be 50%, which is a simplification of the real urban environment. The default setting for the subject used by the WWW Calculator is selected, which is 70.0kg weight, 0.6 clo clothing insulation, and 58.2W/m^2 metabolic rate. A temporal course of 60 min exposure time is calculated. The option of *Transient Values* is selected, meaning that the subject's thermal condition for each minute is calculated.

In parallel, same values are calculated using the implemented TNM model. In practice, this is easily done by assigning a "virtual walk" for a person agent. The walk is set to have a length of 60 steps, with each step representing 1 minute's course. The person agent's thermal condition is therefore updated for each step. Values calculated include skin temperature (T_{skin}), core temperature (T_{core}), respiratory evaporative heat loss (E_{res}), respiratory sensible heat loss (C_{res}), dry heat loss from skin surface (DRY), total evaporative heat loss at skin surface (ESK), and skin blood flow (SKBF). There are other values that are possible to be calculated, nevertheless they can all be derived based on the above mentioned parameters, so for the purpose of the verification, these 7 values should be enough for comparison with the WWW Calculator. For E_{res} and C_{res}, both methods give the same results, being two constant values during the temporal course, which are 3.76 (W/m^2) and 0.326 (W/m^2) respectively. The comparisons of the other values which vary temporally are plotted. Due to the page limitation, only the cases for T_{skin} and T_{core} are shown (Figures 2 and 3). Other parameters show similar results.

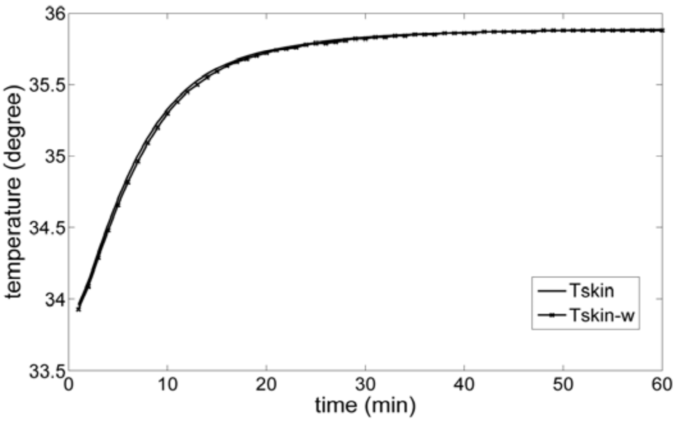


Figure 2: Comparison between TNM and WWW Calculator: skin temperature (T_{skin}). The value calculated by TNM is denoted as T_{skin}, and the value calculated by the WWW Calculator is denoted as T_{skin-w}.

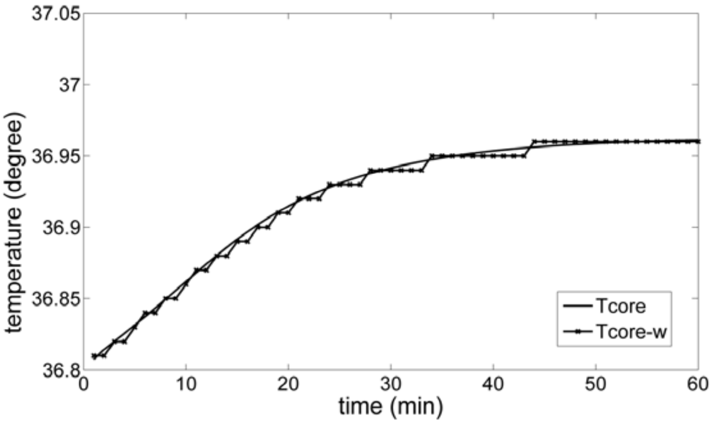


Figure 3: Comparison between TNM and WWW Calculator: core temperature (T_{core}). The value calculated by TNM is denoted as T_{core}, and the value calculated by the WWW Calculator is denoted as $T_{core\text{-}w}$.

It can be seen from the figures, that the results calculated by the two methods agree with each other very well. Therefore, the correctness of the TNM implementation is verified.

4.2. A real-world walking scenario

This section shows, through a real-world case study, the effectiveness of the dynamic assessment and the applicability of the computational system. A densely built-up downtown area is selected as the study site. The site has the size of 500 m × 500 m. Differences in building height and density are commonly found in the domain. The thermal assessment concerns a summer afternoon case. The meteorological condition of the simulated day is summarized in Table 2.

Table 2: Summary of meteorological condition of the simulated day.

Date	Modeling period	T (°C)	Radiation (W/m2)	RH (%)	Sunshine (hour)
9, May, 2008	14:00-15:00	30	500	65	10.5

A simple short-distance walking scenario is simulated to illustrate the idea of monitoring the thermal transient process of a single person while he/she walks in the urban environment. The origin point, destination point and path of the walking are shown in Figure 4. The path is about 130 m long with various shading and sunny conditions. Therefore, diverse thermal comfort conditions of the person are expected to be observed. A “standard object” (male, 40 yrs, 1.75 m, 75 kg, 1.2 m/s walking speed) is selected and monitored. The subject is initially set to have a core temperature (T_{core}) of 36.8 °C, and a skin temperature (T_{skin}) of 33.7 °C, as the neutral state. Detailed temporal physiological condition variation of the subject is shown in Figure 5. In parallel, the subject’s steady state is also calculated, including his steady state core temperature ($T_{core\text{-}st}$) and steady state skin temperature ($T_{skin\text{-}st}$). The subject’s local radiation, as describe by the Mean Radiant Temperature (T_{mrt}) and his PET value are calculated based on the local meteorological condition and shown for reference.

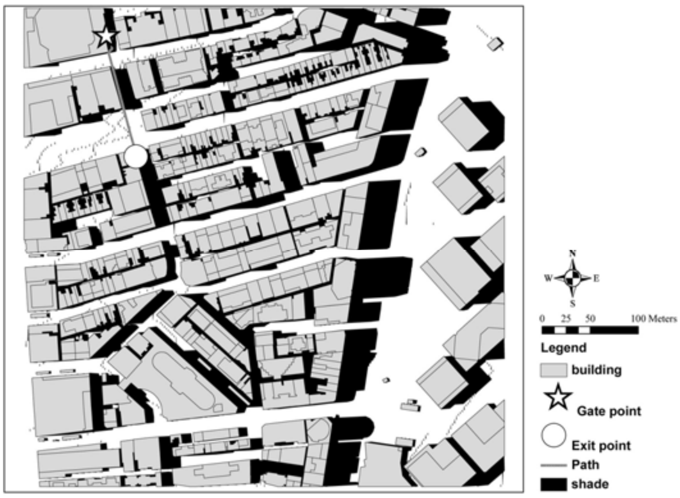


Figure 4: A map showing origin, destination and path of the walking scenario.

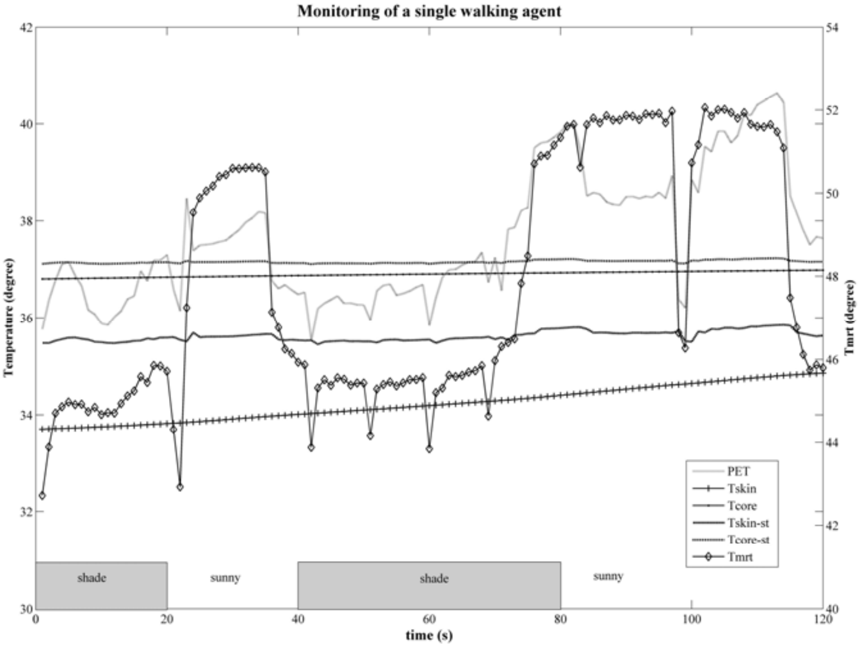


Figure 5: Temporal variation of a walking agent's thermal transient process.

As shown in Figure 5, during the 120 second walking in the urban environment, the pedestrian's thermal stress is quite high, with T_{skin} increasing from 33.7 °C to 34.8 °C, which is still substantially lower than the steady state ($T_{skin-st}$) of ~35.5°C under the given climatic condition. Under shaded area, the pace of the increase is relatively lower, as illustrated by the course from 40 s to 80 s where the temperature changing rate is 9.44×10^{-3} °C/s; whereas under insolation, the pace is higher, as the courses from 20 s to 40 s, and 80 s to 100 s, with temperature changing rate being 1.02×10^{-3} °C/s and 1.22×10^{-3} °C/s, respectively. This changing rate difference is consistent with the spatial variation of T_{mrt}. On the other hand, T_{core} shows a much slower changing rate, which is only increased by 0.18 °C after the walking and is constantly 0.2 to 0.3 °C lower than the steady state. This suggests that under hot condition, the core part of human body has a much slower adaptation rate compared with the skin part. The simulation result also clearly shows that the thermal adaptation process of a pedestrian is dynamic, and the pedestrian is constantly in an un-steady state, therefore steady-state models are not suitable in this case. This conclusion also confirms the findings by Höppe (2002).

5. CONCLUSION

This paper presents a bottom-up simulation approach to model pedestrian's thermal transient process along walking. A modified Two-Node Model is implemented to assess pedestrian's thermal comfort condition. The model is verified with models in the literature. With a simple real-world walking scenario, the system confirms that steady-state models are not suitable for assessing pedestrian's dynamic thermal adaptation. Notably, because of the individual-based feature of the system, it is straightforward to "probe" the detailed thermal condition of a selected subject. Indeed, a lot of other thermoregulatory indictors, such as clothing temperature, skin blood flow, sweating rate and net metabolic heat production can all be investigated using the system. Admittedly these indicators are not quite informative for people without domain knowledge in climatology and physiology, which is commonly the case for planners; nevertheless, given that there is still lack of commonly accepted methodology for dynamic thermal assessment, a combination of these indicators, such as the examples demonstrated above, can suffice to depict to a substantial degree the dynamic course of pedestrian's dynamic thermal adaptation process.

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